

Lunar occultations of 184 stellar sources in two crowded regions towards the galactic bulge. ★

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ABSTRACT

Context. Lunar occultations (LO) provide a unique combination of high angular resolution and sensitivity at near-infrared wavelengths. At the ESO Very Large Telescope, it is possible to achieve about 1 milliarcsecond (mas) resolution and detect sources as faint as $K \approx 12$ mag.

Aims. We have taken advantage of a passage of the Moon over two crowded and reddened regions in the direction of the inner part of the galactic bulge, in order to obtain a high number of occultation light curves over two half nights. Our goal was to detect and characterize new binary systems, and to investigate highly extincted and relatively unknown infrared sources in search of circumstellar shells and similar peculiarities. Our target list included a significant number of very late-type stars, but in fact the majority of the sources was without spectral classification.

Methods. A LO event requires the sampling of the light curve at millisecond rates in order to permit a detailed study of the diffraction fringes. For this, we used the so-called burst mode of the ISAAC instrument at the Melipal telescope. Our observing efficiency was ultimately limited by overheads for telescope pointing and data storage, to about one event every three minutes.

Results. We could record useful light curves for 184 sources. Of these, 24 were found to be binaries or multiples, all previously unknown. The projected separations are as small as 7.5 mas, and the magnitude differences as high as $\Delta K = 6.5$ mag. Additionally we could establish, also for the first time, the resolved nature of at least two more stars, with indication of circumstellar emission. We could also put upper limits on the angular size of about 165 unresolved stars, an information that combined with previous and future observations will be very helpful in establishing a list of reliable calibrators for long baseline interferometers.

Conclusions. Many of the newly detected companions are beyond the present capabilities of other high angular resolution techniques, however some could be followed up by long baseline interferometry or adaptive optics. From estimates of the stellar density we conclude that, statistically, most of the companions are not due to chance alignments.

Key words. Techniques: high angular resolution – Occultations – Stars: binaries: general – Stars: fundamental parameters – Stars: circumstellar matter – Infrared: stars

1. Introduction

Lunar occultations (LO) are simple, economic, time efficient, and they provide high angular resolution far exceeding the diffraction limit of any single telescope. In fact the resolution of LO is matched at present only by long-baseline interferometry (LBI), which however is far from being simple, economic or time efficient. At a large telescope, LO also offer a superior sensitivity. Clearly LO have significant limitations of their own, in particular the fact that they are fixed time events of sources selected randomly by the apparent lunar motion. Another important limitation is the fact that a single LO event only provides information along the direction of the limb motion, i.e. it is intrinsically one-dimensional. This can be overcome if more events of the same source are observed, either from different locations or in the course of different lunar passages. Admittedly, this is difficult to achieve if a large telescope is to be employed. On the other hand, it is worth mentioning a significant bonus of the LO technique, namely the possibility to apply statistical methods that yield the actual brightness profile and not just a diameter or a binary separation. This makes LO ideal to study sources with complex geometries.

Given the characteristics and limitations of LO, this method is best suited for routine observations of large samples of targets with the aim of serendipitous detections of binary stars and resolved sources. At a large telescope where observing time is precious, there are essentially two ways to implement this strategy: wait for favorable episodes in which the Moon covers a large number of sources in a brief period of time (see Richichi et al. 2008a, 2008b), or obtain small chunks of observing time whenever they become available (see Richichi et al. 2010). These three latter references (Paper I to Paper III, respectively) include a detailed description of how the LO method has been implemented at the ESO Very Large Telescope (VLT), both in terms of instrumental solutions, of observational strategy, of data reduction, and of performance. Thus, in the present paper we will linger only very brief on these aspects, and concentrate instead on the results and the conclusions.

2. Observations and Data Reduction

Following the strategy of maximum return for minimum observing time, we observed the passage of the Moon over two crowded regions rich in near-infrared sources during the two first half nights of September 25 and 26, 2009. As in the previous papers we used ISAAC, this time at the Melipal telescope (UT3). The instrument was operated in burst mode, reading out a 32×32 pixels ($4''.7 \times 4''.7$) subwindow with a time sampling of 3.2 ms which was also the effective integration time. We used mostly sequences of 5000 frames, or 16 s, per star. In a few cases we chose slightly shorter or longer sequences to manage situations of occultations very close to each other in time, or cases of two sources occulted within the same field of view (see Sect. 3.3). A broad band K-short filter was employed for most of the sources, except for three bright stars for which we used a narrow band filter centered around $2.07 \mu\text{m}$ to avoid saturation. All events were disappearances, with a lunar phase of about 49% and 59% in the two nights. The seeing was generally good with extremes of

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* Based on observations made with ESO telescopes at Paranal Observatory

Table 1. Statistics of observations

Night	25 Sep, 2009	26 Sep, 2009
Duration	4 ^h 22 ^m	5 ^h 03 ^m
Sources	86	98
Average RA	18 ^h 05 ^m	18 ^h 58 ^m
Average Dec	−25°32′	−23°48′
Airmass min	1.02	1.00
Airmass max	2.69	2.79
Average seeing	0′67	0′72
K min (mag)	2.74	4.60
K max (mag)	8.97	10.86
K median (mag)	6.74	8.52
Average J-K (mag)	2.3	1.0
Binaries & Triples	14	10
Extended sources	2	0

0′44 and 1′1, and we could follow the Moon to a maximum airmass of 2.8. Over the two nights, we recorded 202 events in about 9.5 hours, but a small fraction of data proved to be not usable and in practice we have a total of 184 confirmed light curves. Using the magnitudes from the 2MASS Catalogue, the brightest and faintest star had K=2.7 and 10.9 mag respectively. A summary of the main statistics of the sample is given in Table 1, while a detailed list is provided in Table 2 which follows the same style of Paper III.

The process of extracting LO light curves from the burst mode data cubes and the corresponding analysis has already been described, particularly in Paper I. As before, we used two versions of the data analysis, both a model-dependent and model-independent one (ALOR and CAL respectively, Richichi et al. 1996 and Richichi 1989). Upper limits on the angular sizes of unresolved sources were computed using the approach described in Richichi et al. (1996). One significant innovation in our arsenal of data reduction tools is a method to deal with light curves which appear to exhibit a variable lunar rate, i.e. for which presumably the local limb slope is changing across the duration of the event. This effect is generally quite small, e.g. 1° or 2° over a few tenths of a second, but given the very high signal-to-noise ratio (SNR) of some of our data it is occasionally noticeable. This method, as well as other considerations on lunar limb effects, is part of a separate paper in preparation.

3. Results

The stars of the first night were clustered in a much more interior region of the bulge than those of the second night. The minimum angular distances from the Galactic Center were just under 5° and almost 17° in the two cases. It is then no surprise that the stars occulted in the first night were in general much redder, as shown in Fig. 1. It can be seen that in this case the reddening can be well explained by general interstellar extinction, with A_V of up to more than 15 mag. This is consistent with the map of general extinction in this area derived from dust infrared emission by Schlegel et al. (1998) which show levels of $6 \lesssim A_V \lesssim 30$ for our sources of the first night. On the second night, little or no reddening is observed and the average (J-K) colors are in line with the typical value of

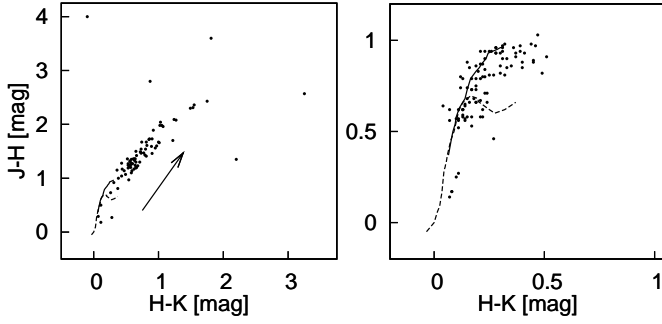


Fig. 1. Color-color diagram for the sources (dots) for which we recorded the LO events listed in Table 2. The left and right panels are for the nights of September 25 and 26, respectively. Note the different scales. The solid and dashed lines are the loci of the unreddened giant and dwarf stars, respectively, according to Bessell & Brett (1988). The arrow is the extinction vector for $A_V=10$ mag, according to Rieke & Lebofsky (1985).

field stars, see Table 1. The table also shows that on the first night the occulted stars were on average significantly brighter than those of the second night: this is the result of the first region being much more crowded, and therefore giving us the opportunity to select occultations of brighter stars in the typical interval of 3 minutes. As mentioned in our previous papers, the number of occultation events to the sensitivity limit of $K \approx 12$ mag far exceeds the practical possibilities of data recording, and we prioritized the events based on K brightness, near-IR colors, and source type and literature entries when available. We note that there is no overlap with the sources included in Papers I to III.

The majority of the targets have near-IR colors consistent with those of giant or dwarf stars after making proper adjustments for extinction, but in few cases more peculiar colors are also observed. We will comment on these, as well as on other cases where the reddening might have circumstellar origins, later in this section. Due also to the reddening, the stars in our sample are generally faint or even undetected at visual wavelengths and are thus relatively poorly studied. Only about 7% have a spectral classification and about 16% have an entry in the Simbad database. Even for these, the available literature is generally very scarce.

In Table 3 we list the sources for which we found a positive result, either as a binary or multiple star or with a resolved angular diameter or with circumstellar emission. For ease of reference, the table is by right ascension and not by time of occultation. It follows a similar format and the same conventions of our previous papers.

We discuss first the sources which were found to be resolved and for which we can provide some context from existing literature, as well as those for which literature entries exist but which we found to be unresolved. We then discuss briefly those without any known cross-identification, and a few relatively wide pairs. Finally, we provide some considerations and general results on the statistics of detected binaries and on the unresolved sources. We do not show all the light curves and their fits. Instead, we provide one example each for a binary, an unresolved and an extended source.

3.1. Sources with known cross-identifications

18022636-2555373 is HD 314951, a $V=9.8$ mag star without bibliographical entries. Its colors suggest either a K5III or a slightly reddened K5V, placing this star in the foreground of our ob-

Table 3. Summary of results.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Source	V (m/ms)	V/V _t -1	$\psi(^{\circ})$	PA($^{\circ}$)	CA($^{\circ}$)	SNR	Sep. (mas)	Br. Ratio	Comments
18022636-2555373	0.2599	-10.7%	-3.3	133	58	119.1	9.9 ± 0.2	25.0 ± 0.1	$K_1=6.0, K_2=9.5$
18023182-2539066	0.5331	-9.8%	-18.0	48	-27	207.2	22.1 ± 0.2	152.2 ± 1.6	$K_1=5.2, K_2=10.7$
18024042-2549567	0.4613	-7.2%	-5.7	104	28	60.6	40.2 ± 0.5	58.8 ± 1.5	$K_1=7.2, K_2=11.6$
18025652-2532392	0.5723	3.1%	3.7	51	-23	160.4	20.5 ± 0.2	76.6 ± 0.8	A-B: $K=5.6, 10.3$
18025652-2532392	0.5723	3.1%	3.7	51	-23	160.4	127.7 ± 0.3	173.2 ± 2.0	A-C: $K=5.6, 11.2$
18032656-2526103	0.4677	2.8%	1.5	28	-46	98.2	17.0 ± 0.5	98.5 ± 2.1	$K_1=7.2, K_2=12.7$
18033522-2523185	0.2700	-20.3%	-6.5	6	-67	108.2	7.3 ± 0.2	57.2 ± 0.9	$K_1=6.4, K_2=10.8$
18040356-2523142	0.3208	-31.3%	-14.6	9	-63	70.7	7.8 ± 0.1	16.1 ± 0.1	A-B: $K=7.0, 10.0$
18040356-2523142	0.3208	-31.3%	-14.6	9	-63	70.7	19.3 ± 0.3	45.8 ± 0.7	A-C: $K=7.0, 11.2$
18040728-2539532	0.6170	-2.4%	-3.5	88	15	149.4	142.2 ± 0.8	418.1 ± 15.3	$K_1=4.9, K_2=11.4$
18041209-2544257	0.4742	-9.7%	-6.4	106	33	17.8			Extended ≈ 4.31 mas
18050733-2543282	0.4660	14.2%	5.7	134	62	71.5	16.6 ± 0.6	91.5 ± 3.0	$K_1=6.7, K_2=11.7$
18050977-2543351	0.5337	37.2%	14.6	145	73	6.2	33.7 ± 1.4	9.5 ± 0.6	$K_1=7.4, K_2=9.9$
18053438-2540309	0.4583	-4.9%	-2.3	120	48	48.6	8.3 ± 0.3	27.7 ± 0.5	$K_1=6.9, K_2=10.5$
18054372-2514234	0.4278	-0.5%	-0.2	15	-57	89.9	10.9 ± 0.2	46.3 ± 0.5	A-B: $K=5.6, 10.3$
18054372-2514234	0.4278	-0.5%	-0.2	15	-57	89.9	24.2 ± 0.2	62.0 ± 0.6	A-C: $K=5.6, 11.2$
18054490-2540399	0.4026	-6.6%	-2.5	126	54	99.6	10.5 ± 0.1	12.6 ± 0.0	$K_1=3.2, K_2=6.0$
18063774-2529277	0.6971	-7%	-8.8	84	12	6.2			Extended ≈ 12.7 mas
18073464-2534117	0.3753	8.1%	2.0	141	69	70.6	37.1 ± 0.2	20.2 ± 0.1	$K_1=5.9, K_2=9.1$
18545320-2357035	0.4844	14.5%	10.3	37	-32	45.6	15.1 ± 0.3	34.2 ± 0.7	A-B: $K=7.9, 11.7$
18545320-2357035	0.4844	14.5%	10.3	37	-32	45.6	12.7 ± 0.5	54.8 ± 1.8	A-C: $K=7.9, 12.2$
18552223-2412461	0.5265	3.6%	4.4	101	31	12.7	43.7 ± 2.9	10.5 ± 0.2	$K_1=9.8, K_2=12.3$
18552401-2349283	0.1628	-19.8%	-3.9	352	-74	41.3	16.6 ± 0.4	14.5 ± 0.1	$K_1=7.6, K_2=10.5$
18553233-2412387	0.4008	-19.0%	-15	85	16	89.2	8.3 ± 0.2	10.4 ± 0.1	$K_1=6.5, K_2=9.9$
18565536-2344580	0.4824	-4.1%	-2.7	22	-42	51.4	13.0 ± 0.8	44.8 ± 1.2	$K_1=7.8, K_2=11.9$
18580265-2337079	0.3949	-24.3%	-13	9	-57	19.9	35.1 ± 2.1	32.8 ± 1.3	$K_1=8.5, K_2=12.3$
19001313-2340112	0.7733	0.7%	1.3	85	19	95.0	17.8 ± 0.4	86.9 ± 2.1	$K_1=6.3, K_2=11.1$
19001602-2349574	0.2667	-16.9%	-4.1	129	63	29.8	13.8 ± 0.5	11.7 ± 0.1	$K_1=7.4, K_2=10.0$
19010885-2317367	0.4861	-16.3%	-7.5	11	-58	7.3	129.6 ± 1.4	1.30 ± 0.01	$K_1=10.4, K_2=10.6$
19011187-2323074	0.8207	1.7%	2.3	46	-22	10.0	34.4 ± 3.3	13.7 ± 0.7	$K_1=9.6, K_2=12.4$

served region. Fig. 2 illustrates our detection both by a model-dependent and a model-independent approach, as used for all the binary stars in this paper.

18041207-2544225 is part of a $3''.9$ wide pair, as detailed in Sect. 3.3. The star to the south, 18041209-2544257, is brighter, with $K=5.59$ mag, and unresolved with an upper limit of 0.50 ± 0.25 mas. It has reliable 2MASS photometric measurements in all JHK bands, and a position coincident with a WISE and a Spitzer detection, with $[5.8]=1310$ mJy and $[8.0]=850$ mJy.

The northern star, 18041207-2544225, appears to be either marginally resolved with an angular diameter of 4.3 mas or, more likely, associated with faint extended emission. Its 2MASS fluxes are uncertain, because of its proximity to the bright star to the south. Its Spitzer fluxes $[5.8]=30$ mJy and $[8.0]=15$ mJy are also unreliable. IRAS detected only one source, 18010-2544 with $[12]=1178$ mJy. If this flux came mostly from the southern source, then this star would have a mid-IR excess.

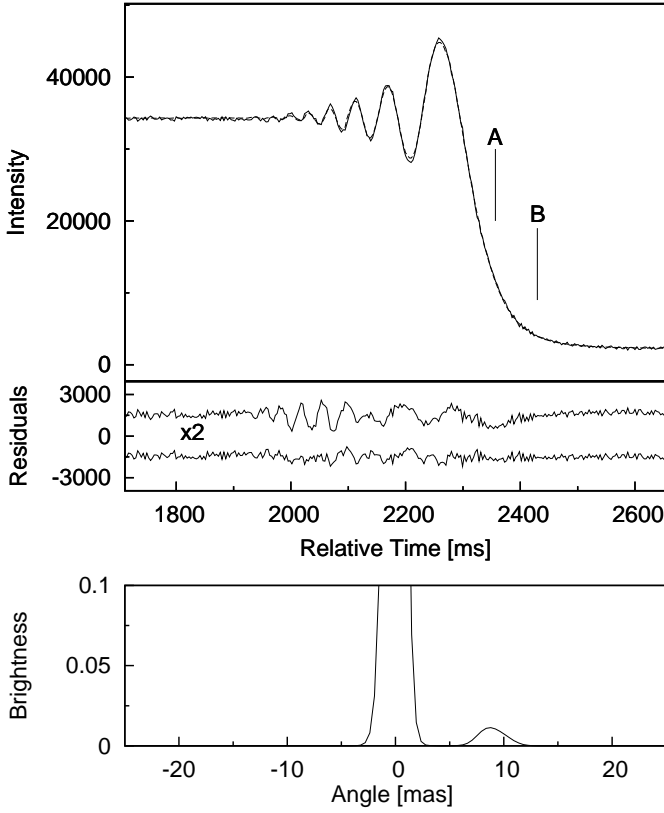


Fig. 2. *Top:* upper panel, data (solid) and best fit (dashed line) for 18022636-2555373. The lower panel shows, displaced by arbitrary offsets and enlarged for clarity, the residuals of the fits by a point-like (above) and by a binary star model including corrections due to slope variations (see text). The normalized χ^2 values are 4.42 and 1.46, respectively. The times of the geometrical occultation of two stars are also marked, with their difference corresponding to a separation of 9.9 mas. *Bottom:* brightness profile reconstructed by the model-independent CAL method.

We stress that the SNR of our LO observation of the northern component is low, ~ 18 . Further observations including spatially resolved near- and mid-IR photometry are needed to confirm and diagnose the nature of the extended emission.

18044848-2536204 is HD 164972, an F2-F3II or F3Ib star (De Medeiros et al. 2002). Its parallax of 2.28 ± 0.89 mas and the absence of significant reddening show it is in the foreground of our sample.

18054372-2514234 is the known bright near-infrared source IRC -30354. Its 2MASS colors, $J-H=1.35$ and $H-K=0.62$, and V magnitude of 13.5 are consistent with a highly reddened late-type dwarf (Hansen & Blanco 1975). The star exhibits a broad H_α line in emission (Velghe 1957). We detect two companions, with small projected separations that place the system at the limit of the resolution for adaptive optics (AO) on a very large telescope, and similarly the large magnitude differences make it challenging for LBI.

18060176-2526099 is IRC -30355, a bright infrared source. Its 2MASS colors are consistent with a late M giant, consistent with its spectral type of M6 determined by Hansen & Blanco (1975). Detected by AKARI, WISE, IRAS, Spitzer and MSX, it has a rising spectral energy distribution with prominent far-infrared excess. Our measurement shows an unresolved source in K band with an upper limit of 0.40 mas.

18063774-2529277 is IRAS 18035-2529, an OH-IR source detected in the 1612 MHz OH maser line, with a typical double-peaked profile (te Lintel Hekkert 1991). It is also a prominent SiO maser source (Deguchi et al. 2004). We note that this star has extreme colors $J-H=2.57$ and $H-K=3.25$ but in fact the 2MASS J-band value is unreliable and the $J-H$ could be even higher. At $K=9.0$ mag this source could not provide a very high SNR by LO. Actually, our detected flux was rather consistent with $K=10.5$ mag, indicating a significant variability which is not unexpected in this kind of source. Both model-dependent and model-independent fits to the data point to a resolved source. In the first case, a formal diameter of 12.7 ± 0.5 mas is derived. The model-independent analysis (Fig. 3) provides however a better normalized χ^2 and is also more consistent with the OH-IR scenario, showing a central star with two asymmetric emission peaks at about 10-20 mas which we attribute to the inner rim of a circumstellar shell.

18545320-2357035 was surveyed by Hipparcos and included as TYC 6860-1491-1 in the re-analysis which led to the Tycho Double Star Catalogue (Fabricius et al. 2002). That the multiplicity was not detected by Hipparcos is consistent with its quoted performance. With $V=10.6$ mag and colors which do not show evidence of significant reddening, this star is probably in the foreground of our sample. We also mention a fainter, relative distant companion (see Sect. 3.3). This was not detected by Hipparcos due to its faintness.

18550997-2401055 is HD 175159, a star for which a LO was previously reported by Evans & Edwards (1983). As in our case, the star was found to be single by these authors.

18570946-2352076 and 18570922-2351582 are CD-24 14860B and HD 175601 respectively, and form a wide visual double system with separations ranging from $10''.3$ (epoch 1910) to $9''.9$ (epoch 1998) (Dommanget & Nys 2002, Mason et al. 2001). Both stars were found unresolved by us.

18580265-2337079 is PPM 734659, a $V=9.9$ mag star for which no literature entries are available. From the relatively bright visual counterpart, the unreddened colors and the high proper motion, we conclude that the star is in the foreground and the $\Delta K=3.8$ mag companion that we detect deserves further investigations for possible orbit determinations.

18594214-2342263 and 18594214-2342263 are AR Sgr and HD 176364, respectively. The former is a G4 star of RV Tau type classified as a very likely post-AGB object by Szczerba et al. (2007), while the latter is a G8IV star. In both cases our non-binarity detection confirms previous results from LO photoelectric observations (Evans & Edwards 1983, Radick et al. 1984).

18071398-2516474 is HD 315178, a known B-type star with a strong H-alpha line in emission (Merrill & Burwell 1950, Velghe 1957). From its 2MASS color, it obviously has an infrared excess and it was detected by MSX at $8\mu\text{m}$ (Clarke et al. 2005). From our measurement we determine an upper limit on its K-band angular size of 1.95 mas.

18072725-2506165 is HD 165517, the optical counterpart of the X-ray source 1RXS J180725.9-250607. This O9.5:Ibe emission-line star has been classified also as B0:Ia by Johnston et al. (1994). With an estimated distance of 2.1 kpc (Kozok 1995) it is in the foreground of our sample. We do not detect any circumstellar emission and the source appears unresolved with an upper limit of 1.2 mas.

18073464-2534117 is HD 165530, a star with $V=8.3$ mag and spectral type G7III which has colors consistent with those of a giant without any significant reddening. Indeed, the Hipparcos parallax places it at 340 pc albeit with a large error (HIP 88798). The fact that our newly detected

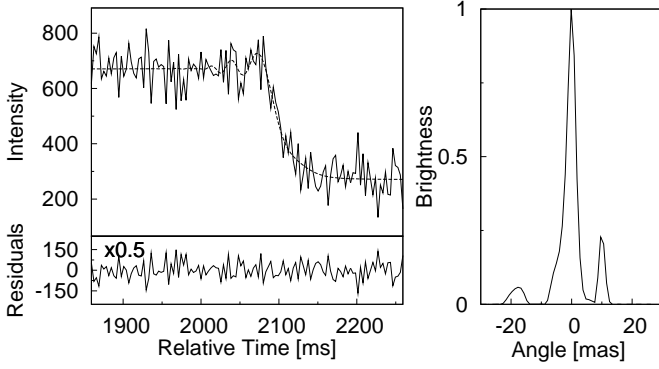


Fig. 3. *Left:* upper panel, data (solid) and best fit (dashed line) for 18063774-2529277. The lower panel shows the residuals of the fit by the profile shown to the right. The normalized χ^2 is 1.21. *Right:* brightness profile reconstructed by the model-independent CAL method.

companion was not revealed by Hipparcos is consistent with the performance limits of this latter (Mignard et al. 1995). We note that an inconsistency was found in the object type and literature references that the Simbad database associates to HD 165530. This is erroneously classified as a star in double system with a components separation of about $13''.3$ and linked to Gahm et al. (1983). By double checking with archive images from several surveys, we noticed that the former reference is actually for HD 165530B, which effectively corresponds to the well-known WDS J18089-2528 double system with the above mentioned components separation.

A few more sources in our sample also have Simbad cross identifications, however without bibliographical entries of any relevance.

3.2. Resolved sources without known cross-identifications

The remaining entries in Table 3 have no known cross-identification in the Simbad database. They include an additional 17 new binaries and 2 new triples, with projected separations spanning the range 7-140 mas. Based on 2MASS, the primaries have K magnitudes ranging from 3.2 to 10.4, and the companions from 6.0 to 12.4. Thus, this sample of binaries represents a good hunting ground for follow-up studies. Although some of the sources might prove beyond the possibilities of present techniques, in many cases either AO or LBI should be able to detect and study the systems. The distribution in terms of projected separation and magnitude differences is shown in Fig. 4.

We mention that 19010885-2317367 is of some interest: it has components of almost equal brightness and with a projected separation of $0''.13$ it should be quickly resolved with a variety of methods. Given that the source appears rather unreddened ($J-H=0.27$, $H-K=0.11$) it is probably a not too distant physical pair.

The large distances to many of our sources, as implied by their substantial interstellar reddening, and the relative crowding of the two regions open the question of whether the binaries that we report are physical pairs or chance alignments. We have computed the average cumulative stellar density as a function of magnitude in the two areas. In the most crowded one, this amounts to 6.9×10^{-4} and 3.0×10^{-3} stars with $K \leq 10$ and ≤ 12 mag respectively, per square arcsecond. The ISAAC subwindow size is about 22 sq. arcsec, but our effective field of view is much smaller. In the direction of the lunar motion we only analyze data equivalent to few $0''.1$ on the sky, since larger separations can be detected by conventional imaging. In the perpendicular direction, we are

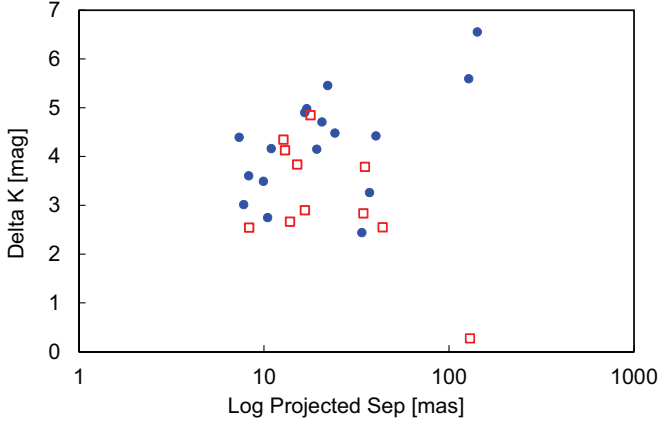


Fig. 4. Distribution of the secondary and tertiary companions in our sample, with respect to their respective primaries. The filled circles and empty squares represent the sources observed in the nights of Sep 25 and 26, respectively. Note that our analysis did not extend beyond about $0''.15$, and that the wide pairs of Table 4 are not included.

limited by the extraction mask which is typically less than half of the subwindow. Although these quantities vary for each event, our effective field of view is in practice $\lesssim 1$ sq. arcsec. Therefore, we do not expect any significant fraction of chance associations in our sample. The probability of finding companions such as those listed in Table 3 is on average 0.1% in the first night, and even less in the second night.

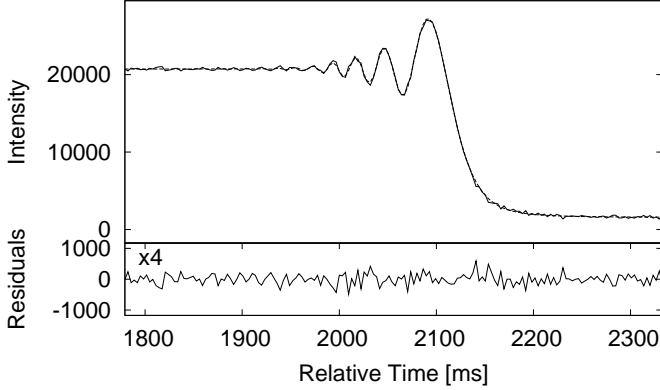
3.3. Wide binaries

In six cases, our acquisition images showed two sources present in the same $4''.7 \times 4''.7$ field of view. By proper positioning in the subwindow and adjustment of the number of frames we could record occultation events for both. They were all observed in the broad K filter. These pairs are unresolved by 2MASS and therefore only one set of J,H,K magnitudes is available, with the exception of the pair 18041209-2544257 and 18041207-2544225 already discussed in Sect. 3.1 for which however the 2MASS magnitudes of the fainter star are unreliable. From our LO analysis we could derive an accurate brightness ratio in the K-band for all these pairs, from which we deduce the individual K magnitudes using the 2MASS total value. For the above 2MASS-resolved pair, we adopted the 2MASS magnitude for the brighter source and derived that of the fainter one from its counts.

To compute separation and position angle (PA) values an average image was created from the occultation frames, and two-dimensional Gaussian PSF fitting (Bertin & Arnouts 1996) was used to find precise positions for the binary components. By comparing values obtained with different centroiding algorithms, we estimate accuracies of better than $0''.05$ and 1° for separation and PA, respectively. The parameters for these wide pairs are listed in Table 4. The suffixes 1 and 2 are in order of disappearance and not of brightness. In Table 2 we can report only the total J and H magnitudes for each pair. Note that some of the individuals components of these wide pairs were additionally found to be resolved, binary or triple as already reported above.

Table 4. Parameters for the wide pairs

2MASS	Sep (")	PA (°)	K ₁ (mag)	K ₂ (mag)
18030887-2535164	1.83	359	7.13	8.28
18041207-2544225	3.94	354	9.41	5.59
18050977-2543351	2.27	35	7.36	11.30
18062439-2525353	2.30	208	10.14	7.33
18545320-2357035	1.59	20	7.89	11.07
18580265-2337079	2.80	280	9.37	9.06

**Fig. 5.** Same as the left side of Fig. 3, for 18012777-2538123 with an upper limit on the angular size of 0.75 mas. The residuals are enlarged and the normalized χ^2 is 1.01. More details in Sect. 3.4.

3.4. Unresolved sources, variability and performance

As in previous papers, we used the χ^2 -based procedure described in Richichi et al. (1996) to assess whether a source was unresolved, and determine an upper limit on its angular size. These upper limits vary with SNR, being on average 2.2 mas and reaching 0.25 mas in the best case. This was computed for 165 sources, but we note that we are not including in this count the individual components of binaries and multiples.

An example of a source established to be unresolved is given in Fig. 5, for 18012777-2538123 observed under average seeing conditions in the first night. This source has no known cross-identifications or literature entries. With $K=6.6$ it falls close to the median brightness of our sample, and with $\text{SNR}=110$ it is representative of a good data quality although by no means exceptional: our sample includes many cases of better SNR, up to about 300. The $(J-K)=1.8$ is consistent with the average color of the sample and suggests no intrinsic reddening. Fig. 5 shows the fit with a point-like source, with a normalized $\chi^2 = 1.013$. We compute an upper limit of 0.75 ± 0.30 mas. For comparison, a fit with a 2 mas model increases the normalized χ^2 by 12.5%.

So far we have adopted the 2MASS K magnitudes at face value, but we should now comment that these might occasionally be inaccurate in two respects. Firstly, by converting our observed counts to a K magnitude using the ISAAC specific response, we notice that about 9% of the sources are up to 1 mag brighter than the 2MASS values, and about 17% are at least 0.3 mag and up to almost 2 mag fainter. We assume here that up to 0.3 mag dimming could be due to airmass and our masking process. Thus variability is an important factor, a fact perhaps not surprising when we consider that most of the sources are probably late-type giants. Indeed, the most extreme case of

flux deficit is that of 18063774-2529277 already commented in Sect. 3.1. Secondly, some of the 2MASS magnitudes are flagged as unreliable, due for example to the presence of a nearby bright star. This applies to three of the most extreme points in Fig. 1, namely 18063720-2514416 with $J-H=4.00$ and $H-K=-0.10$, 18043132-2527356 (2.80, 0.87) and 18024090-2552007 (1.35, 2.20).

In Papers I to III we have already reported details on the performance of sensitivity and angular resolution of the LO method at the ESO VLT. Without further figures we state here that also for the present data we confirm an angular resolution ranging from ≈ 0.5 mas for $\text{SNR} > 100$ to ≈ 5 mas for $\text{SNR} \approx 10$. These SNR values are typically achieved for K magnitudes of ≈ 5 and ≈ 10 , respectively. A comparison with the early predictions on LO performance at a very large telescope using subarrays (Richichi 1994) shows that a significant improvement could still be gained in sensitivity, by using instruments with a pixel size matching the seeing disk.

We also note that, adding to the previous statistics reported in Papers I to III, we have now a database of about 350 unresolved stars with reliable upper limits as small as 0.25 mas, determined in a consistent fashion using LO at the VLT. The range of magnitudes and of sizes represents an ideal catalog of calibrators for near-IR LBI, to which we can add the substantial number of resolved and binary stars which were not previously known and that can be likewise flagged as non suitable calibrators. This database is still increasing thanks to further observations currently under analysis, and we plan to publish it in the near future.

4. Conclusions

Using the LO technique with the ISAAC instrument at the ESO VLT, we have carried out milliarcsecond resolution observations of 184 sources in two crowded regions towards the galactic bulge. The stars in the first of these two regions were as close as 5° from the Galactic Center and exhibited very significant interstellar extinction. The second region was further away and less extinguished. While most of the sources had colors that could be reconciled with reddened dwarf or giant late-type stars, some objects appeared to have outstanding colors. In general, the majority of the sources in our sample have no optical counterpart and very few have spectral determinations or bibliographical entries.

We detected 20 new binary and 4 new triple systems. The projected separations are as short as 7 mas and the brightness ratios as high as $\Delta K=6.5$ mag. Some of these systems could be followed up in principle by other high angular resolution techniques but many others would require a combination of sensitivity and angular resolution which can only be obtained at present by LO. We also detect two sources which appear to be resolved on the milliarcsecond scale, one of them being a OH-IR star, and the other being in a pair which shows a spectral energy distribution rising in the infrared.

We have evaluated the probability of finding chance associations from the average cumulative stellar density in the two regions of our sample, and we found that for the given separations and magnitude differences the probability is extremely low.

With this paper we have increased the number of unresolved stars with reliable upper limits in the milliarcsecond range, observed in a homogeneous way with the same instrument and method, to about 350. This list, to be further extended with more observations currently under analysis, can serve as a useful reference catalogue for interferometric calibrators.

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Table 2. List of the recorded occultation events

2MASS id	Date	UT	J	H	K	Sp	Cross-Id
18012777-2538123	25-09-09	23:14:10	8.35	7.10	6.56		
18014156-2539527	25-09-09	23:19:44	9.41	7.82	6.93		
18015800-2549077	25-09-09	23:25:04	9.42	7.53	6.61		
18020084-2543076	25-09-09	23:28:49	9.51	7.85	6.85		
18014561-2536014	25-09-09	23:31:22	10.41	8.32	7.08		
18020469-2553488	25-09-09	23:35:55	8.89	7.57	7.01		
18015392-2534372	25-09-09	23:40:36	9.27	7.55	6.70		
18023182-2539066	25-09-09	23:54:50	7.44	5.94	5.22		
18024042-2549567	25-09-09	23:59:45	9.74	8.01	7.15		
18022636-2555373	26-09-09	0:01:47	6.97	6.24	5.98	K5	HD 314951
18024090-2552007	26-09-09	0:03:42	12.45	11.10	8.90		
18015464-2529273	26-09-09	0:05:36	9.39	7.35	6.32		
18024492-2535538	26-09-09	0:08:21	8.62	7.52	6.94		
18022315-2530237	26-09-09	0:11:33	10.12	8.16	7.08		
18030392-2542136	26-09-09	0:14:25	9.65	7.97	7.16		
18030699-2543447	26-09-09	0:16:26	9.18	7.51	6.77		
18030504-2536574	26-09-09	0:19:25	8.18	6.64	5.84		
18025652-2532392	26-09-09	0:22:03	7.35	6.15	5.60		
18030887-2535164-1	26-09-09	0:24:15	8.74	7.39	7.13		
18030887-2535164-2					8.28		
18030533-2532570	26-09-09	0:26:25	6.77	5.46	4.90		
18032159-2538369	26-09-09	0:28:31	6.87	5.73	5.26		IRAS 18002-2538
18032661-2538323	26-09-09	0:31:54	8.97	7.61	7.08		
18033221-2541506	26-09-09	0:34:32	12.80	9.20	7.40		
18033459-2544130	26-09-09	0:36:54	9.29	7.79	7.14		
18033362-2547375	26-09-09	0:39:47	8.17	6.61	5.66		IRAS 18004-2547
18030885-2527400	26-09-09	0:43:18	6.65	5.41	4.88		
18034631-2533153	26-09-09	0:49:56	7.29	5.99	5.28		IRAS 18006-2533
18035693-2539570	26-09-09	0:51:48	7.32	5.96	5.33		
18035200-2547316	26-09-09	0:54:43	10.25	8.52	7.62		
18032656-2526103	26-09-09	0:56:37	11.02	8.71	7.18		
18040728-2539532	26-09-09	0:58:54	7.08	5.65	4.86		
18033401-2525313	26-09-09	1:02:11	8.84	7.48	6.84		
18041209-2544257	26-09-09	1:05:19			9.41		
18041207-2544225	26-09-09	1:05:24	8.63	6.66	5.59		IRAS 18010-2544
18042112-2533526	26-09-09	1:10:12	7.99	6.71	6.28		
18033522-2523185	26-09-09	1:12:42	8.40	7.04	6.43		
18043026-2541466	26-09-09	1:15:59	8.55	7.01	6.29		
18043001-2531141	26-09-09	1:18:06	7.92	6.45	5.68		
18041530-2525329	26-09-09	1:20:33	5.42	4.62	4.24	K5	HD 315063
18040356-2523142	26-09-09	1:22:36	9.01	7.59	6.93		
18043132-2527356	26-09-09	1:24:10	11.31	8.51	7.64		
18044848-2536204	26-09-09	1:26:16	5.99	5.70	5.63	F2/F3II	HD 164972
18044287-2544318	26-09-09	1:29:56	7.68	6.41	5.82		

Table 2. continued.

2MASS id	Date	UT	J	H	K	Sp	Cross-Id
18044594-2527198	26-09-09	1:32:17	9.60	8.13	7.41		
18045257-2528135	26-09-09	1:34:29	10.22	8.25	7.19		
18045371-2524226	26-09-09	1:41:35	6.19	4.94	4.37		IRAS 18018-2524
18051090-2529257	26-09-09	1:43:14	9.75	8.14	7.18		
18050733-2543282	26-09-09	1:47:21	8.42	7.24	6.71		
18050977-2543351-1	26-09-09	1:49:47	9.70	8.24	7.36		
18050977-2543351-2					11.30		
18052039-2524573	26-09-09	1:53:44	9.83	8.13	6.91		
18053347-2537524	26-09-09	1:56:51	8.70	7.49	6.85		
18052602-2523384	26-09-09	1:58:38	8.17	7.00	6.57		
18053438-2540309	26-09-09	2:01:33	8.73	7.53	6.87		
18054382-2537288	26-09-09	2:03:33	8.86	7.63	6.95		
18052646-2520179	26-09-09	2:05:31	9.98	8.38	7.56		
18054490-2540399	26-09-09	2:10:07	4.95	3.67	3.15		
18060176-2526099	26-09-09	2:13:53	4.28	3.13	2.77	M6	IRC -30355
18055576-2540082	26-09-09	2:17:18	5.93	4.96	4.42		
18054212-2543196	26-09-09	2:20:54	6.77	5.59	4.94		IRAS 18026-2543
18061707-2523008	26-09-09	2:24:46	8.36	7.08	6.50		
18062439-2525353-1	26-09-09	2:26:21	11.43	9.00	10.14		
18062439-2525353-2	26-09-09	2:26:21	11.43	9.00	7.33		
18054372-2514234	26-09-09	2:30:17	4.72	3.36	2.74	M8+	
18063774-2529277	26-09-09	2:32:49	14.79	12.22	8.97		IRAS 18035-2529
18061354-2515305	26-09-09	2:36:23	8.74	7.41	6.78		
18065092-2529560	26-09-09	2:40:40	5.97	5.06	4.75	M	HD 315192
18065490-2530316	26-09-09	2:43:21	9.01	7.71	7.07		
18063720-2514416	26-09-09	2:47:27	12.09	8.09	8.19		
18064787-2514557	26-09-09	2:51:10	9.52	7.85	6.85		
18064977-2537355	26-09-09	2:53:14	8.29	7.10	6.53		
18071918-2524448	26-09-09	2:55:55	7.54	6.54	6.16		
18071398-2516474	26-09-09	2:59:12	8.46	8.19	7.91		HD 315178
18072061-2517190	26-09-09	3:01:32	9.18	6.87	5.38		
18063098-2509319	26-09-09	3:04:08	7.33	6.29	5.87		IRAS 18034-2509
18072731-2532426	26-09-09	3:06:38	8.02	6.85	6.23		
18074347-2524288	26-09-09	3:08:58	7.02	5.78	5.14		
18071147-2509208	26-09-09	3:13:48	9.55	8.09	7.35		
18073464-2534117	26-09-09	3:16:25	6.44	5.94	5.83	G7III+...	HD 165530
18074951-2532392	26-09-09	3:22:19	8.01	6.60	5.78		IRAS 18047-2533
18081328-2523474	26-09-09	3:24:52	6.77	5.70	5.21		
18081825-2521370	26-09-09	3:27:06	8.74	7.60	7.01		
18072725-2506165	26-09-09	3:29:38	7.15	6.97	6.86	BIa	HD 165517
18082752-2518296	26-09-09	3:32:12	10.66	8.59	7.32		
18083425-2523306	26-09-09	3:36:04	11.66	9.31	7.76		
18543875-2403222	26-09-09	23:23:26	6.95	6.06	5.72		CD-24 14823
18550100-2408394	26-09-09	23:30:15	9.36	8.38	8.07		

Table 2. continued.

2MASS id	Date	UT	J	H	K	Sp	Cross-Id
18541928-2358016	26-09-09	23:32:31	10.51	9.65	9.35		
18551118-2413072	26-09-09	23:36:52	8.83	7.86	7.39		
18550780-2403564	26-09-09	23:41:25	7.44	6.54	6.23		
18552223-2412461	26-09-09	23:46:11	10.37	9.80	9.66		
18550997-2401055	26-09-09	23:48:36	7.37	6.79	6.58	K1III	HD 175159
18545320-2357035-1	26-09-09	23:51:43	8.54	8.01	7.89		TYC 6860-1491-1
18545320-2357035-2					11.07		TYC 6860-1491-1
18553233-2412387	26-09-09	23:54:53	7.94	6.91	6.44		
18553706-2411230	26-09-09	23:58:20	10.69	9.76	9.54		
18550303-2355559	27-09-09	0:00:52	8.87	8.06	7.81		
18554320-2411418	27-09-09	0:03:48	10.03	9.41	9.19		
18553293-2359253	27-09-09	0:06:37	9.02	8.09	7.72		
18554220-2415597	27-09-09	0:09:11	9.65	8.76	8.32		
18550756-2354134	27-09-09	0:10:21	8.55	7.82	7.65		
18554874-2401474	27-09-09	0:12:40	9.07	8.15	7.74		
18554945-2400538	27-09-09	0:14:28	10.20	9.56	9.42		
18555913-2403339	27-09-09	0:17:56	10.04	9.17	8.96		
18555632-2400073	27-09-09	0:20:14	11.20	10.46	10.30		
18561680-2406431	27-09-09	0:30:12	10.40	9.66	9.46		
18555737-2354145	27-09-09	0:33:27	8.37	7.44	7.14		
18561788-2358243	27-09-09	0:36:56	11.31	10.52	10.39		
18562006-2357173	27-09-09	0:40:04	11.15	10.31	10.15		
18553777-2349547	27-09-09	0:42:05	10.71	9.86	9.53		
18552401-2349283	27-09-09	0:43:57	8.79	7.84	7.56		
18563747-2408447	27-09-09	0:49:24	10.73	9.88	9.65		
18563774-2410374	27-09-09	0:53:15	8.95	8.04	7.67		
18564920-2400465	27-09-09	0:56:10	10.99	10.21	10.02		
18564563-2354023	27-09-09	1:01:11	10.98	10.09	9.86		
18565387-2355147	27-09-09	1:04:24	8.88	8.14	7.95		
18570282-2358475	27-09-09	1:06:57	9.23	8.28	8.03		
18564695-2349245	27-09-09	1:11:43	10.90	10.24	10.06		
18561672-2345402	27-09-09	1:14:04	11.40	10.61	10.40		
18570432-2351321	27-09-09	1:16:26	10.15	9.21	8.96		
18570946-2352076	27-09-09	1:18:26	9.57	9.40	9.32		CD-24 14860B
18570922-2351582	27-09-09	1:18:33	9.42	9.28	9.21	A1V+...	HD 175601
18570262-2410283	27-09-09	1:21:48	8.92	8.21	7.98		
18565615-2346249	27-09-09	1:24:19	10.71	10.09	10.03		
18572854-2402401	27-09-09	1:27:10	6.51	5.57	5.18		
18565536-2344580	27-09-09	1:28:41	8.98	8.14	7.74		
18572506-2348190	27-09-09	1:33:49	5.92	5.09	4.60		
18574519-2354457	27-09-09	1:38:20	9.74	8.87	8.65		
18573657-2405454	27-09-09	1:40:56	9.65	9.03	8.90		
18574575-2349490	27-09-09	1:43:03	8.77	7.97	7.86		
18575364-2400373	27-09-09	1:46:05	8.92	8.11	7.79		

Table 2. continued.

2MASS id	Date	UT	J	H	K	Sp	Cross-Id
18573272-2343187	27-09-09	1:48:57	10.89	10.01	9.86		
18575391-2345582	27-09-09	1:53:22	8.96	8.01	7.73		
18580998-2355311	27-09-09	1:55:33	10.56	9.98	9.85		
18580488-2403296	27-09-09	2:03:58	10.91	10.10	9.83		
18580978-2343262	27-09-09	2:06:01	9.61	8.65	8.35		
18581661-2343555	27-09-09	2:08:40	9.35	9.18	9.09	F2V	HD 175851
18580940-2340445	27-09-09	2:11:24	6.48	5.53	5.22		IRAS 18551-2344
18581647-2340114	27-09-09	2:15:48	8.22	7.34	6.89		
18580265-2337079-1	27-09-09	2:18:59	9.08	8.52	9.37		
18580265-2337079-2					9.06		
18582165-2338403	27-09-09	2:21:34	8.87	8.32	8.21		
18585453-2349519	27-09-09	2:26:02	6.49	5.51	5.07		
18585782-2351145	27-09-09	2:28:29	10.65	9.91	9.79		
18585736-2342464	27-09-09	2:31:53	8.59	7.74	7.55		
18581996-2334007	27-09-09	2:35:20	10.48	9.91	9.80		
18591262-2346443	27-09-09	2:38:07	11.69	11.01	10.86		
18591792-2350546	27-09-09	2:42:38	10.11	9.50	9.37		
18583937-2332312	27-09-09	2:45:54	9.14	8.34	8.12		
18592407-2341426	27-09-09	2:47:34	8.69	7.86	7.66		
18593674-2346506	27-09-09	2:53:35	11.12	10.31	10.08		
18592411-2335094	27-09-09	2:55:58	10.46	9.83	9.78		
18594214-2342263	27-09-09	2:57:23	8.41	7.95	7.68	G4	AR Sgr
18585553-2329395	27-09-09	3:00:45	10.12	9.50	9.39		
18585480-2329085	27-09-09	3:02:56	9.75	9.23	9.12		
18593194-2355053	27-09-09	3:05:03	9.39	8.48	7.97		
18595823-2339176	27-09-09	3:08:09	9.50	8.83	8.65		
18595396-2334060	27-09-09	3:11:17	10.78	9.84	9.61		
19000813-2343368	27-09-09	3:13:02	11.61	10.88	10.71		
19001313-2340112	27-09-09	3:16:07	7.63	6.66	6.27		
18595891-2331159	27-09-09	3:17:55	9.50	8.57	8.29		
19001505-2348245	27-09-09	3:22:45	10.17	9.50	9.30		
19002907-2340467	27-09-09	3:25:28	9.17	8.58	8.45		
19001602-2349574	27-09-09	3:28:15	8.47	7.61	7.27		
19000444-2326074	27-09-09	3:30:58	9.39	8.81	8.60		
19004442-2339386	27-09-09	3:34:32	7.88	7.00	6.60		
19003871-2330374	27-09-09	3:36:30	10.09	9.48	9.34		
19005121-2333311	27-09-09	3:39:53	10.82	10.17	10.03		
19004262-2326331	27-09-09	3:44:04	8.18	7.60	7.43		CD-23 14943
19002919-2323136	27-09-09	3:46:23	10.93	10.27	10.08		
19004796-2324055	27-09-09	3:50:42	8.88	8.10	7.93		
19011673-2332578	27-09-09	3:53:21	10.06	9.13	8.86		
19012148-2332350	27-09-09	3:55:59	10.55	9.89	9.73		
19012789-2336241	27-09-09	3:59:28	8.84	8.02	7.72		
19011187-2323074	27-09-09	4:01:26	10.21	9.63	9.49		

Table 2. continued.

2MASS id	Date	UT	J	H	K	Sp	Cross-Id
19012308-2342339	27-09-09	4:03:49	9.14	8.18	7.81		
19014063-2332313	27-09-09	4:06:08	9.61	9.03	8.88		
19005076-2317221	27-09-09	4:11:11	7.37	6.80	6.69	G8IV	HD 176364
19010885-2317367	27-09-09	4:13:26	10.12	9.85	9.74		
19015719-2335001	27-09-09	4:16:07	9.14	8.18	7.87		
19015242-2339279	27-09-09	4:18:56	8.66	7.94	7.71		
19013557-2316469	27-09-09	4:22:49	9.59	9.34	9.25		
19021893-2330540	27-09-09	4:26:44	9.51	8.85	8.61		

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‘18022636-2555373’ on page 4	‘18041209-2544257’ on page 9
‘HD 314951’ on page 4	‘18041207-2544225’ on page 9
‘18041207-2544225’ on page 5	‘18012777-2538123’ on page 10
‘18041209-2544257’ on page 5	‘18012777-2538123’ on page 10
‘18041207-2544225’ on page 5	‘18063774-2529277’ on page 11
‘18010-2544’ on page 5	‘18063720-2514416’ on page 11
‘18022636-2555373’ on page 6	‘18043132-2527356’ on page 11
‘18044848-2536204’ on page 6	‘18024090-2552007’ on page 11
‘HD 164972’ on page 6	
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‘IRAS 18035-2529’ on page 7	
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‘18570922-2351582’ on page 7	
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‘18594214-2342263’ on page 7	
‘18594214-2342263’ on page 7	
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‘HD 176364’ on page 7	
‘18071398-2516474’ on page 7	
‘HD 315178’ on page 7	
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‘1RXS J180725.9-250607’ on page 7	
‘18073464-2534117’ on page 7	
‘HD 165530’ on page 7	
‘HIP 88798’ on page 7	
‘18063774-2529277’ on page 8	
‘HD 165530’ on page 8	
‘HD 165530B’ on page 8	
‘WDS J18089-2528’ on page 8	